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NATURE-BASED DEVELOPMENT LAKE BARDAWIL

Regenerating Lake Bardawil
A Nature-Based Approach to Coastal Ecosystem Regeneration

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Abstract - *Coastal ecosystems like Lake Bardawil are critical to biodiversity, food security, and local livelihoods, yet they face increasing degradation due to climate change, overexploitation, and habitat disruption. This study outlines a regenerative strategy for restoring Lake Bardawil, a shallow coastal lagoon on Egypt's northern Sinai coast, through Nature-based Solutions (NbS) that mimic natural processes to enhance ecological resilience and socio-economic development.*

The project focuses on restoring the lake's hydrological and morphological balance by improving tidal exchange with the Mediterranean Sea. Key interventions include dredging and optimizing the two main inlets (Boughaz 1 and 2), constructing tidal gullies and wetlands, and reinforcing the sand spit that separates the lake from the sea. These measures aim to increase the tidal prism, the volume of water exchanged during tidal cycles, thereby enhancing water quality, reducing salinity, and increasing flow velocity. These hydrodynamic improvements are expected to stabilize the inlet system, support nutrient cycling, and facilitate fish migration, ultimately regenerating the aquatic food web.

The first phase of the ecological restoration is projected to already significantly boost fish populations, with annual catches increasing from approximately 4,250 to 17,000 tons over ten years under the P50 scenario. This growth offers substantial socio-economic benefits for local communities, including job creation and regional economic stability. However, the project's success depends on addressing technical and market-related factors such as dredging costs, soil characteristics, carbon sequestration potential, and price distortions from subsidies and unemployment.

To ensure long-term sustainability, the initiative emphasizes responsible fisheries management, including catch quotas and ecosystem monitoring. By aligning ecological restoration with economic incentives, the Lake Bardawil project presents a scalable model for regenerative coastal development that benefits both nature and society.

Index Terms - Coastal regeneration, Coastal ecosystem restoration, Regenerative design, Nature-based solutions, Lake Bardawil, Morphological stability, Aquatic food web, Socio-economic development, Tidal Prism, Salinity Reduction, Sustainable fisheries.

INTRODUCTION

Coastal ecosystems are essential foundations of ecological and economic value. They are sustaining the planet's biodiversity and supporting human societies that rely on their resources. However, widespread degradation, in the form of pollution, overexploitation, and climate change, threatens these ecosystems' ability to provide food security, livelihoods, and coastal protection (Nichols et al., 2019).

Regenerating coastal ecosystems is vital for restoring the services they provide to human societies. "Regenerative" means processes that restore, renew or revitalize their own sources of energy and materials. Regenerative design uses whole systems thinking to create resilient and equitable systems that integrate the needs of society with the integrity of nature.

This document elaborates the implementation of a regenerative strategy at Lake Bardawil, a shallow coastal lagoon on the northern coast of the Sinai Peninsula in Egypt (Figure 1). The lake's aquatic ecosystem forms the basis of income for the people living around it, harbouring an important fishing industry vital for the local communities. In the business-as-usual scenario, preservation of the fragile ecosystem is at risk due to morphological changes (sedimentation of the two major inlets and erosion of the barrier) and human activities impacting the lake's habitats and fish population.

Mimicking natural processes is what we strive to achieve by our engineering interventions to initiate and facilitate a series of natural recovery processes in and around the lake, nature will drive the restoration. These so-called Nature-based Solutions (NbS) to societal challenges are solutions that are inspired and supported by nature, which are cost-effective, provide environmental, social and economic benefits and help build resilience.

Figure 1. Overview of Lake Bardawil and its two major inlets Boughaz 1 in the West and Boughaz 2 in the East.

PROBLEM DEFINITION

Lake Bardawil thanks its existence to the thin sand spit that separates the lake from the Mediterranean Sea. This barrier creates the lake and its remarkable ecological habitat, a hotspot for migrating birds and several vulnerable species. To ensure the future of the ecosystem and the communities living from it, the preservation of the sand spit is essential.

Severe erosion of the sand spit, leading to weak spots, seems to occur along the barrier, for example direct east of both Boughaz 1 and 2. The erosion is predominantly caused by the hard structures (breakwaters and revetments) that obstruct the natural longshore sediment transport, causing sedimentation in the inlets. In the 1980's, it was decided to address the sedimentation problem in the inlets with the construction of breakwaters in addition to the already present rock revetments. These interventions minimized the abrupt sedimentation in the inlets, creating more stable conditions, but only in the short term. Currently, constant maintenance is required to keep the connections between Lake Bardawil and the Mediterranean Sea open, while the fundamental water quality issues and associated aquatic ecosystem decline are not solved.

The high air temperatures and low humidity in combination with the present wind climate in the North Sinai area cause high evaporation rates in Lake Bardawil; on average over 2 million m3 of water each day. Not only must this volume of water be compensated with extra inflow from the Mediterranean Sea, but it also causes high salinity values within the lake, impacting the water quality.

The lake's water quality and fish habitat have been greatly decreased over the past decades resulting in a steady decline of available fish to catch. On top of that, overfishing and poor management of the lake's habitat (e.g., seagrass) has led to further reduction in the fish population. The lower yield of the fishing industry causes financial strain on the growing population around the lagoon (Said, 2022).

OBJECTIVE

Restoring the aquatic ecosystem of Lake Bardawil and its surrounding areas in a sustainable and holistic way is central to the project's objective, aiming to support a thriving fish population, strengthen biodiversity, and drive socio-economic development in the region. The objective is visualised in Figure 2, explaining the interventions, threats and mitigation measures. The interventions should aim to improve the integrity of the system, by reinforcing the coast of the sand spit, and to aim for morphological stability to keep maintenance costs low.

On the right-hand side of the figure the main identified threats to the project in relation to human influences are listed. It is crucial to obtain detailed understanding of trends and underlying causes and processes present in and around Lake Bardawil. This is of essence to successfully achieve the objective of restoring the lake to significantly contribute to the socio-economic development of the region.

The ecosystem regeneration interventions are deemed to result in an increase in tidal energy input into the lake. The works comprise of the implementation of Nature-based Solutions (NbS), such as the construction of tidal inlets, gullies and wetlands. Tidal lagoon systems, such as Lake Bardawil, will always be subject to sedimentation and erosion processes, but this should support and not harm the functionality of the optimized design. The objective of these interventions is to increase the primary production and thus the total biomass within a robust and diverse food web. This should lead to a larger fish population and make way to regenerative fish catch.

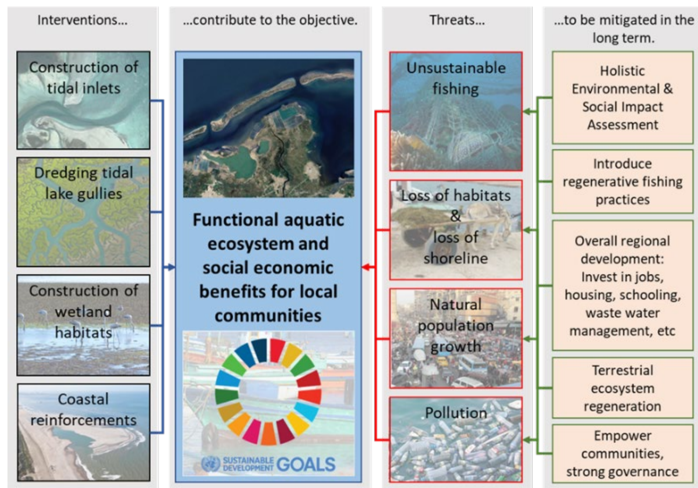

Figure 2. Illustration of the project objective and main influences.

This document focuses on the Phase 1 technical interventions identified within the proposed development plan, as these are considered key drivers in the ecological recovery of the lake. The Phase 1 works aim to restore the lake's morphological and hydrological balance, laying the foundation for a healthier ecosystem and a more resilient fish population. The methodology and broader vision behind these interventions are detailed in the following section. In parallel, a cost-benefit analysis has been initiated to assess the economic viability of these measures, providing early insights into their potential returns and helping to guide future investment decisions.

REGENERATION METHODOLOGY LAKE BARDAWIL

As in any ecosystem, the primary source of energy is sunlight. Through the process of photosynthesis, solar energy is harnessed to convert nutrients into biomass. Additionally, tidal energy plays a crucial role in shaping the environmental conditions that support primary production, as the tides drive key processes such as:

- Flushing the lake to obtain and maintain a certain water quality for primary production (e.g. salinity, temperature, dissolved oxygen);
- Creating water level variations and helical (spiral) flows for the recycling and fluxes of nutrients, facilitated by habitats, such as seagrass beds and salt marshes.

Ecosystem regeneration in the Lake Bardawil system requires attention on both the current unsustainable harvesting in the ecosystem (guaranteeing a balanced system) as well as the forming a solid ecosystem foundation (increasing the size of the ecosystem), visualised in Figure 3.

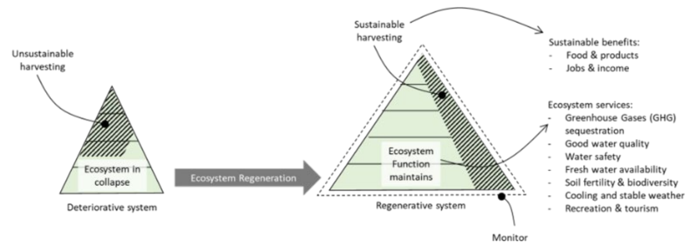

Figure 3. Diagram showing the concept of ecosystem regeneration and the transition from a deteriorative system to a regenerative system.

Regenerative fish management ensures a more biodiverse aquatic ecosystem, which will increase the food web efficiency and the natural productivity of the system. This can be achieved by establishing catch quota in the form of diverse catch, minimum size of catch and focus on overpopulation as well as creating dedicated protected areas.

Lake Bardawil's key fish species, including seabream (Sparus aurata), seabass (Dicentrarchus labrax and Dicentrarchus punctatus), and mullets (Mugilidae species), migrate between the lake and the Mediterranean Sea. Most spawning occurs in the Mediterranean; while feeding and growth take place in the lake. Although the broader ecological context is acknowledged, the project will focus specifically on fisheries management within Lake Bardawil.

To safeguard the ecological integrity of Lake Bardawil while benefiting from its ecosystem services, it is essential to implement regenerative fishing and aquaculture practices. The project aims to develop a sustainable fisheries management strategy in close collaboration with local stakeholders. A comprehensive monitoring program will be established to collect essential data, including fisheries-dependent information such as landings per unit effort and catch composition, and fisheries-independent data such as fish size, abundance, and carrying capacity indicators. These monitoring activities will be carried out with active involvement from the local community.

In case of aquaculture development in the lake, it should aim to achieve zero environmental impact. This requires careful planning to ensure that aquaculture activities do not compromise the lake's ecological value. Species selection should align with environmental conditions, the availability of juveniles and suitable feed, and market demand. Opportunities linking aquaculture with existing local fisheries should also be explored.

Proposed Design

The proposed design, illustrated in Figure 4, integrates all four interventions within the Lake Bardawil system. The implementation is structured in two stages: an initial phase and the full-scale deployment of the project, so:

- **Phase 1** Deepening and widening of the two present inlets Boughaz 1 and 2
- **Full scope** New West, New Mid and inner lake gullies

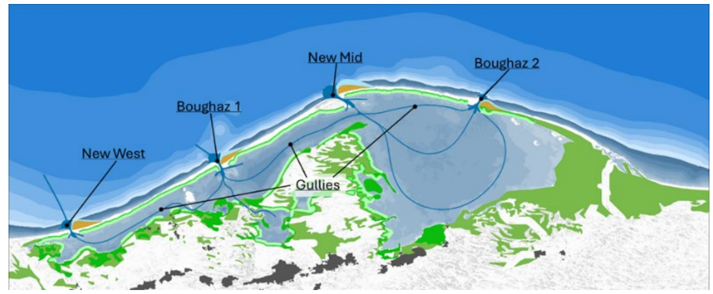

Figure 4. Proposed design for Lake Bardawil system consisting of the four inlets, tidal gullies and wetlands.

The first phase consists of the deepening of the present inlets, including removal of the breakwaters with the addition of side gullies adjacent to the inlets facilitating the incoming and outgoing flow. The sediments dredged during this operation will be used to create emerged and submerged shoals and beach nourishments adjacent to the inlets, reinforcing the sand spit at vulnerable locations. They layout of such a sand engine is given in Figure 4, which also gives a close-up of the inlet design of Boughaz 1.

Following the first phase, two additional inlets named New West and New Mid are constructed to enhance tidal energy exchange in the more stagnant zones of Lake Bardawil. These inlets are connected to the main lake through a network of gullies that improve water circulation, reduce salinity levels, and support better overall water quality. The fine sediment produced by these dredging activities is then used to create new wetlands along the shoreline, further contributing to habitat restoration and ecological resilience.

Interventions

The Mediterranean tide governs the water exchange between Lake Bardawil and the Mediterranean Sea and is characterized by a semi-diurnal, micro-tidal regime. Due to this connection the water level inside Lake Bardawil fluctuates up and down according to the tidal motions outside of the lake. To facilitate the increase in tidal elevation within the lake, the volume of water entering and leaving the system during each tidal cycle must increase as well. This process is also known as the tidal prism and functions as an important parameter for evaluating the impact of the proposed interventions.

The primary design interventions consist of the construction of tidal inlets, the dredging of tidal lake gullies to facilitate the tides and using the excess material of these interventions for the construction of wetland habitats and coastal reinforcements. The philosophy of these interventions is further discussed in this section.

Tidal inlets

The relation between the characteristics of the tidal inlet, such as cross-sectional area, and the interaction between the

Mediterranean Sea and Lake Bardawil forms the basis of the stability of a tidal inlet. Inlet stability is often described as dynamically stable or unstable, due to the dynamic nature of the coastal area, where migration of sediment is a natural occurrence. Two stability relations, Escoffier (1940) and Bruun & Gerritsen (1960), are presented to describe the dynamic stability of a tidal inlet and will be used in this study to assess the status of both Boughaz 1 and Boughaz 2 for the Baseline scenario and Phase 1. Escoffier (1940) determines the stability of an inlet with the relation between the depth averaged equilibrium velocity and the cross-sectional area of the inlet, where Bruun & Gerritsen (1960) assess the stability by the ratio between the littoral drift and the tidal prism.

Dredging the present inlets as well as developing additional inlets stimulates the water exchange between the Mediterranean Sea and the lake and thus increases the tidal prism. Enhanced water exchange improves the water quality (lower salinity, lower water temperatures, …) and attracts more migrating fish, facilitated by deeper foreshore gullies to the open sea (Wageningen Marine research, 2016). Nutrient rich sediments are brought into suspension, becoming available into the foreshore, attracting additional fish from the Mediterranean Sea for migration into the Lake Bardawil.

Tidal lake gullies

Tidal gullies inside the lake will improve the connectivity and circulation patterns inside the lake. Interaction between gullies and inlets further propagates tidal energy into the lake and provides increased water level variations and dynamics at the lake shores further away from the inlets. The relatively deeper gullies also provide habitat variation in the lake, making way for the larger predator fish to migrate into the lake.

Wetland habitats

Regenerating the historical wetlands in and around Lake Bardawil holds significant ecological and socio-economic value. These wetlands provide vital habitats that support the broader marine ecosystem and create long-term stability and prosperity for nearby communities. Halophyte plants, which flourish in saline environments, contribute substantial belowground biomass, up to four times greater than their aboveground production (Curcó et al., 2002). When these roots die and decompose, they add organic matter to the soil and transform the wetlands into effective carbon sinks. Salt marshes rank among the most efficient natural systems for carbon sequestration, alongside mangroves and seagrasses. This process is sustained by tidal action, which continuously deposits clay and silt sediments rich in nutrients and organic materials onto the marsh soils.

Creating new wetlands through the reuse of fine sediments dredged from the gullies contributes to both ecological restoration and nutrient management around Lake Bardawil. They facilitate the deposition of resuspended sediments on the tidal flats, which helps recycle nutrients and increases silica availability supporting aquatic productivity. In addition, the restored wetlands serve as nursery grounds that help sustain and grow juvenile fish populations. When combined with the strategic planting of salt-tolerant vegetation, these actions collectively enhance the resilience and ecological function of the marine environment. Two types of potential wetlands are distinguished:

- Inland wetlands: These wetlands will be situated in natural low-lying areas (depressions) situated more inland mainly south of the lake, but in the vicinity of the lake's shoreline. A total of 33 km2 of potential inland wetland area is identified as suitable for development and/or reinforcement.
- Shoreline wetlands: On the lake's shorelines a total of 65 km2 is identified suitable for wetland development. The area consists of 11 km2 of high marsh, 15 km2 of low marsh and 39 km2 of mudflats.

Sand spit reinforcements

Maintaining the stability of the sand spit is essential to safeguard the long-term integrity and safety of the entire system. The construction of the NbS tidal inlet is expected to enable a natural sand bypass, which should significantly reduce or halt further erosion. However, targeted sand nourishment on the eastern side of the inlets will still be necessary to reinforce and stabilise the coastline. The beach nourishments at each inlet will be constructed from the (sandy) dredged material as visualised in Figure 5. The design consists of a submerged sand shoal in combination with an emerged beach nourishment:

- The emerged zone captures the main wave driven currents and causes a water setup that increases the tidal inflow and therewith the tidal prism. A minimum increase of 2% was found by (Georgiou, 2019);
- The submerged zone facilitates natural sediment bypassing by allowing spiral flows within the main inlet to overflow around its outer edge, while the prevailing littoral drift largely continues past the entrance. Residual tidal eddies are important for the sediment transport processes and the water exchange of the system (Bosboom & Stive, 2022), (Yang & Wang, 2013);
- The submerged berm dissipates the wave energy which improves the wave energetic conditions, important for the redistribution of the sediment along the coast (Luijendijk, et al., 2017);

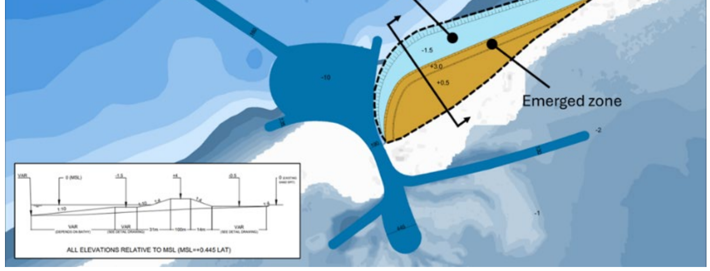

Figure 5. Principle of the sand engine foreseen at the inlets, with a submerged and an emerged zone.

In addition to the above consideration, it is also expected that the beach nourishments will further reinforce the coast eastwards. These expectations are based on the experience in the Sand Engine pilot project at the Dutch coast. This structure was primarily developed to feed the adjacent coast with the required annually sediment budget (de Schipper, et al., 2014) and the requirements of multi stakeholders about several aspects such as nature development (Luijendijk, et al., 2017).

PHASE 1 IMPACT OF INTERVENTIONS

Methodology

The system modelling aims to predict the increase in biomass during the design and validate the projected increase during the execution. We make a clear distinction between the baseline scenario, being the Baseline (the business-as-usual scenario without proposed project interventions) and the impact after interventions.

The overall objective of the ecological modelling is to predict the biomass and species distribution of the aquatic ecosystem in relation to the baseline in order to facilitate the regenerative fish management approach and control the project's environmental and social impact. A study is conducted on the Phase 1 design, consisting of the interventions at Boughaz 1 and Boughaz 2, using the numerical modelling software D-Flow FM, the D-Water Quality (Deltares, 2022) and a dedicated habitat model.

The origin of the Phase 1 dredging design lies in a multitude of iterations of regeneration scenarios for Lake Bardawil, in which also the impact of one and two additional inlets were assessed in several orientations and compositions. (Lanters, 2016), (Georgiou, 2019), (van Bentem, 2020), (Bangen, 2021), (Panagopoulos, 2022) and (Hoek, 2023), carried out different hydrodynamic studies to analyse the hydrodynamic, morphodynamical and ecological responses to the interventions.

Hydrodynamic Results

This section gives the modelling results of the response of Lake Bardawil on the interventions of Phase 1, consisting of the dredging of the present two inlets Boughaz 1 and 2 (Figure 6) with the addition of sand engines, in relation to the Baseline scenario. Followed by the impact of the interventions on the fish catch potential of the lake.

Figure 6. Phase 1 of the Bardawil Development Project consisting of the dredging of Boughaz 1 and Boughaz 2.

For salinity, the differences between Baseline and Phase 1 can be made clear by expressing what percentage of the lake has a value between a given data range. This allows for a numerical observation on areas where spatial changes are not that noticeable. An analysis of the interaction between the Mediterranean Sea and Lake Bardawil shows a significant increase in tidal prism after the implementation of Phase 1, where a volume growth of 77% is given, see Table 1.

Table 1. Monthly average tidal prism in million m^3 for Baseline and Phase 1 and the respective difference.

Scenario	Tidal Prism Boughaz 1 [Mm3]	Tidal Prism Boughaz 2 [Mm3]	Total Tidal Prism [Mm3]	Increase in Tidal Prism
Baseline	18.6	20.9	39.5	-
Phase 1	28.3	41.6	69.9	77%

The impact of the interventions on the salinity concentration within Lake Bardawil is shown in Figure 7, with a data range between 38 ppt and 58 ppt. For the Baseline (a) a large area of the lake remains dark red, indicating a salinity value exceeding 58. After the interventions to the inlets (b) the salinity decreases, and the predominant north-western winds are clearly visible in the result, with large patches of lower salinity waters infiltrating the eastern basin. The overall mean salinity for August drops by 3.3 ppt relative to Baseline after one year of simulation.

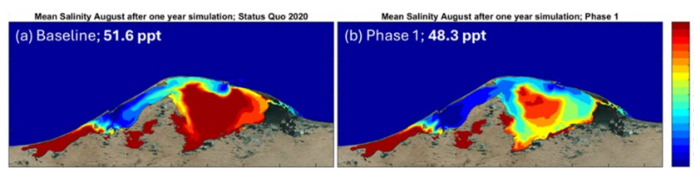

Figure 7. Mean Salinity in August after one year of simulation, for Baseline (a) and Phase 1 (b).

The impact of the interventions on the salinity is best shown with the lake volume percentage between given values (Table 2). While the overall salinity drops with 3.3 ppt, the water volume with a value exceeding 58 ppt is reduced from 49% to 16%. Figure 7 shows that these volumes, after Phase 1, mainly reside in the western and inner lagoon areas, difficult to reach by the incoming tide due the shallow nature of Lake Bardawil.

Table 2. Area of Lake Bardawil that corresponds with a given salinity, comparing Baseline and Phase 1.

Scenario	38 - 40	40 - 42	42 - 44	44 - 46	46 - 48	48 - 50	50 - 52	52 - 54	54 - 56	56 - 58	> 58
Baseline [%]	2	5	6	5	6	3	4	5	8	7	49
Phase 1 [%]	6	9	7	9	9	10	11	9	11	3	16
Change [%]	4	4	1	4	3	7	7	4	3	-4	-33

Inlet stability

Following Bruun (1978), a velocity magnitude below 1 m/s indicates an inlet experiencing sedimentation, while inlets exceeding 1 m/s result in inlet erosion. The inlet velocities determined by the numerical simulations for the two assessed scenarios are given in Table 3. For Baseline, both inlets experience a velocity magnitude below the threshold value of 1 m/s, indicating a naturally closing inlet, which is supported by a sensitivity analysis. Thus, the inlets are considered dynamically unstable and will close without intervention.

Table 3. Maximum observed cross-sectional averaged inlet velocities [m/s] for Baseline and Phase 1.

Scenario	Maximum cross-sectional averaged inlet velocity Boughaz 1 [m/s]	Maximum cross-sectional averaged inlet velocity Boughaz 2 [m/s]
Baseline	0.85	0.80
Phase 1	1.08	1.09

The Phase 1 design shows promising results, with both inlets yielding a maximum cross-sectional averaged inlet velocity close to 1.1 m/s, surpassing the critical velocity of Bruun (1978). The velocity magnitude indicates a natural growth in inlet size until a stable dynamic equilibrium is reached.

The Bruun and Gerritsen (1960) stability value highly depends on the magnitude of the littoral drift, therefore two scenarios based on values from literature are used to assess the stability of the inlets for both scenarios. A value below 50 indicates poor inlet stability and a value exceeding 50 indicates fair to good stability, depending on the magnitude. Baseline yields fair stability for the low estimate and poor stability for both inlets looking at the high littoral drift estimates (Table 4), this corresponds with the sedimentation trend and required maintenance dredging currently taking place at the inlets. Phase 1 brings a significant increase in spring tidal prism to both inlets, where even during high littoral drift situations both inlets are at least classified with a fair stability. The low drift estimate classifies them as good.

Table 4. Bruun & Gerritsen Inlet Stability assessment based on the spring tidal prism and littoral drift estimate.

	Boughaz 1		Boughaz 2	
Scenario	**Baseline**	**Phase 1**	**Baseline**	**Phase 1**
Spring Tidal Prism	25.5 Mm^3	38.4 Mm^3	28.2 Mm^3	56.4 Mm^3
High littoral drift estimate	35	53	39	78
Low littoral drift estimate	85	128	94	188

Hence, the numerical model simulation places both inlets on a favourable location on the Escoffier closure curve, indicating a dynamic stable equilibrium inlet system which requires limited maintenance dredging. The Bruun and Gerritsen stability shows a similar trend where a significant increase in the stability value is observed.

Ecology

The increased inflow of (re-suspended) nutrients into Lake Bardawil resulting from the amplified tidal prism will increase the primary production and thus exerts a bottom-up pressure on the ecosystem. Higher primary production leads to an increase in herbivore biomass, which grazes on the primary production. However, if left unchecked, the herbivore population might overgraze, resulting in reduced ecosystem productivity or even collapse of the ecosystem. The herbivore population can be controlled by a sufficiently large predator group, which exerts a top-down pressure on the ecosystem. The influx of (large) predator fish from the Mediterranean Sea into the lake might cause an unsustainable top-down pressure on the herbivore population due to overeating. This results in a deficit in the herbivore population and thus a lack of food for the predators. Effective management of both bottom-up and top-down pressures can accelerate the establishment of a new ecosystem balance.

An ecological model is built to estimate biomass growth of key fish species within Lake Bardawil's ecosystem and uses algorithms to predict the distribution of a species across geographic habitats and time using the hydrodynamic boundary conditions. Each habitat has unique hydraulics, depth and species. The species can move from one habitat to another. In the example of Figure 8, the ecosystem is divided in three different habitats (A, B and C).

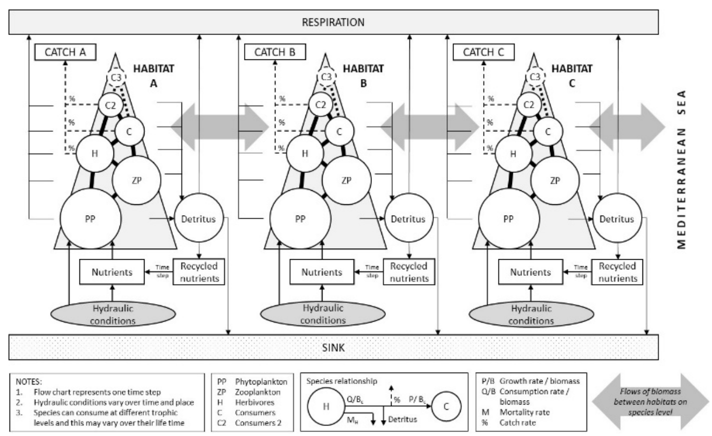

Figure 8. A graphical overview of the correspondence between the different habitats and how the biomass of groups is related to each other. The PP circle represent the primary production which is related to the (changing) influx of nutrients. The arrow leaving the pyramids represent the outflow of energy through mortality and fish catch, while the horizontal arrows represent the flows of biomass between the separate habitats. In this example three different habitats are included (A, B and C), but this can be increased in the model.

Potential regenerative catch

The habitat model is used to analyse the effect of proposed dredging interventions and fish management programs on the biomass levels, and thus the overall health of the ecosystem. The model is setup that it determines the optimal catch to achieve the maximum growth of the food web over time (in this case 10 years) for different fish catch scenarios. As a rule of thumb, only 10% of the energy in one trophic level will reach the next trophic level (Lindeman, 1942). The model allows to move past this rule of thumb and calculate biomass more precise. This is also desirable for calculating the fish catch of individual species and to understand the interconnectedness between all species within the food web of Lake Bardawil. With the current availability of field data, it is difficult to validate the baseline modelling results, however the expected fish catch is in line with the statics of relevant reference lagoons within the Mediterranean basin. It should be noted that the fish catch potential of lake Bardawil highly depends on lake management.

The interventions improve the morphological behaviour, water quality and ecological conditions of the lake. Growth of the high trophic aquatic food web forms the basis of an increase in potential fish catch yields which will significantly contribute to the socio-economic development of the region. In the P50 scenario, the fish catch can grow from 4,250 ton/yr to approximately 17,000 ton/yr in 10 years following the implementation of Phase 1, see Figure 9. The fish catch with a confidence level of P90 was found to be 12,250 ton/yr, and, with a confidence level of P20, a potential value of 21,700 ton/yr was found for year 10 after start of the works.

Revenues from fish catch are the main contributor to the project benefits. Currently, Egypt hardly exports fish, and most is used for domestic consumption. It is assumed that the increase in the fish population in the lake and associated growth in job opportunities will find a positive response from the local communities. In the P90 scenario, the annual incremental fish catch compared to the Baseline can grow to over 12,000 tons. Over time the number of direct fishery jobs can grow to a number between 3,000 and 15,000 (depending on the annual landings and crew per vessel which requires further research and validation) and 1,000 – 5,000 secondary jobs (postharvest processing, transport, distribution). In addition to the jobs in the fish industry, the wetlands restoration and maintenance will create tens of job opportunities too.

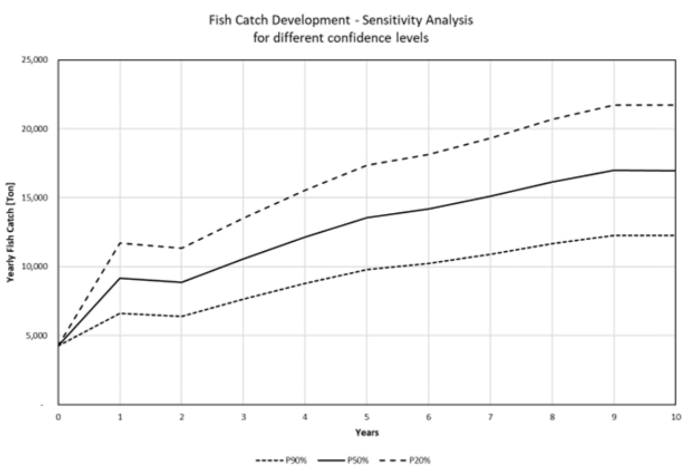

Figure 9. Yearly catch projections modelling 10 years after completion of Phase 1 for confidence levels P90, P50 and P20. The confidence levels are based on an extensive sensitivity assessment for different environmental conditions

Cost-benefit analysis

An initial cost-benefit assessment (CBA) was conducted in October 2023 for Phase 1 of the Bardawil Lake Regeneration Project. The analysis highlights the complexity of the business case, shaped by factors such as dredging costs, tidal prism, fish catch potential, fishing industry profitability, carbon sequestration volumes, and the influence of market distortions like unemployment, fuel subsidies, carbon pricing, and local versus international fish prices. While not aiming to deliver definitive conclusions, the assessment offers a first structured insight into how these variables interact and affect the project's economic viability under different scenarios.

Table 5 below summarizes the results of the CBA under the different confidence levels for the fish catch. The economic analysis of the project is conducted using constant prices. The incremental costs and benefits have been discounted against a Social Discount Rate of 6%.

Table 5. Monetized results of the CBA for the three regenerative fish catch probability scenarios, conducted in 2023

Item	Values		
Local fish price (EUR/kg)	2.5		
Shadow fish price (EUR/kg)	3.75		
Carbon sequestration price (EUR/kg)	75		
Regenerative fish catch scenario	**P90**	**P50**	**P20**
Incremental revenue fish catch (EUR m)	986	1,548	2,115
Carbon sequestration income (EUR m)	210	210	210
Total incremental benefits (EUR m)	1,196	1,758	2,325
Capex Phase 1 (EUR m)	225	225	225
Incremental Fisheries costs (EUR m)	676	1,061	1,450
Baseline maintenance dredging costs (EUR m)	53	53	53
BSI plan maintenance dredging costs (EUR m)	13	13	13
Organizational expenses (EUR m)	41	41	41
Total incremental costs (EUR m)	902	1,287	1,676
Total incremental costs & benefits (EUR m)	294	471	649
Net Present Value (NPV) Benefits (EUR m)	432	639	847
Net Present Value (NPV) Costs (EUR m)	445	587	730
Economic NPV (EUR m)	6	58	122

Reducing uncertainty in the cost-benefit assessment will require further research. This includes targeted data collection through local surveys, in-depth studies, and model validation to identify hidden costs and externalities. It is recommended to map the fisheries supply chain and engage local communities as part of a comprehensive Environmental and Social Impact Assessment (ESIA).

CONCLUSIONS

The economic viability of the project is determined by a combination of technical, ecological, and market-related factors. These include the cost of dredging, the characteristics of the soil, the expected increase in fish catch of higher trophic species, and the profitability of the fishing industry. Additionally, the volumes and actual value of carbon sequestration must be considered, along with the effects of price distortions caused by unemployment, diesel subsidies, and differences between local and international fish prices.

The planned interventions will enhance the tidal wave propagation from the Mediterranean Sea into the Lake Bardawil. This will lead to improved water quality through, among other things, reduced salinity and increased flow velocity. The hydrodynamic changes are expected to create a morphologically stable inlet system and improve nutrient availability, which supports the growth of the aquatic ecosystem. The increased tidal influence will further facilitate the migration of fish from the Mediterranean Sea into the lake, contributing to biodiversity and ecological resilience. The restoration of the marine ecosystem results in a significant increase in fish populations, with notable improvements expected the first year after dredging. This growth will continue over time, supported by improved environmental conditions and the expansion of the aquatic food web.

The projected increase in fish catch, from approximately 4,250 tons per year to around 17,000 tons per year within ten years for the P50 scenario, represents a substantial opportunity for socio-economic development. This growth will support local livelihoods, strengthen regional economies, and contribute to long-term stability. To ensure the long-term sustainability of this development, it is essential to implement responsible fishing strategies. These should include predefined catch quotas and ecosystem monitoring to prevent overfishing and to guide the ecological development of the lake.

The success of the project will depend on the integration of ecological restoration with sound economic planning and sustainable resource management. By aligning environmental objectives with economic incentives, the initiative can deliver lasting benefits for both the ecosystem and the communities that depend on it.

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"The Weather Makers Foundation" has been established to set the plan for a regenerated Sinai in motion. This document has been created in a series with several other articles that detail the plan on Regenerating the Sinai. These documents are distributed freely.

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